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Radiation Hazards

The Turbulent Diffusion of the Radioactive Products in the Sea

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The purpose of this memorandum is to demonstrate that the radiation hazards will be very considerably mitigated by the turbulent diffusion of the products down into the water. The radiation hazards in Shot A may be anticipated small after four hours and may even be tolerable for short times at 2 hours. Even in Shot B, they may be small in 12 hours except possibly for ships near in, and down wind.

The danger from radioactivity may be divided into two classes:

(1) Those arising from the fission products
(2) Those arising from secondary radioactive products induced in the material structure of the ships.

Evidence from the Trinity experiment, and from measurements in Hiroshima and Nagasaki, make it practically certain that (2) will be below the significant level for both shots.

With regard to (1) in Shot A, two possibilities must be considered. The first is that the flame region containing fission products will extend over at least one ship and contaminate it by actual deposition. Here it may be stated that ships which are this close will in all probability sink. Therefore it is unlikely that any ship which still floats will be contaminated by primary products. The second represents the only serious possibility and is that the fission products will condense on the surface of the sea directly, or be condensed on droplets which return to the surface of the sea.

With regard to (1) in Shot B, three possibilities must be considered. The first is direct contamination of a ship by the flame zone; contamination in this way of a ship which does not sink is very small. The second is contamination of a ship by water drops containing radioactive products falling on the ship. This appears a serious possibility for ships near-in down wind. Some trouble may be expected for these ships. The third is the spreading of the fission products over the surface and throughout the volume of the sea within about 1500 feet of the explosion center.

Shot A

We may suppose that in this shot the products are initially spread uniformly over a certain area, estimated roughly at 1000 feet radius. If the products did not move, the radiation density above the water surface in this area would be given by the accepted formula, provided by Weisskopf

$$R(\text{per hour}) = P\,\frac{3200}{T(\text{hours})} \times \frac{n(\text{kilotons})}{m(\text{sq miles})}$$

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where P is the fraction of the fission products actually deposited, n is the energy of the explosion in kilotons, and x square miles is the area over which the products are spread.

Just what the true value of P will be is to some extent a matter of speculation. However, the writer believes with some confidence that P will not exceed 0.001. This value is about one-tenth that found at Trinity. Having regard to the very different heights of burst (600 feet or more as against 100 feet) the value 0.001 is considered a very safe maximum value to assume. Then

$$R(\text{per hour}) = \frac{4000}{T}$$

where T is in hours. This formula may well overestimate R by a factor 10.

Clearly, if the products remained fixed on the surface, it would not be safe to venture into the central area even for a few minutes until two or three days after the explosion have passed.

There are, however, at least two further factors that will considerably reduce the radiation hazards. The first is the turbulent diffusion of the fission products down into the water, where their effect is much reduced, or even completely removed. The second is the carrying away of the products by the tide. The second factor is not altogether material, because the radiation hazard will still remain in the water, although its center will have moved.

For simplicity, consider only diffusion downwards from the surface. The density of radioactive products at depth Y at time T will be

$$R(T)\,(\pi KT)^{-\frac{1}{2}}\,e^{-Y^2/4KT}$$

where R(T) is the radiation density at the surface assuming the products have not moved, and K is the eddy coefficient of diffusion.

Let λ be the mean free path of the γ-radiation in water (actually λ is about 30 cm). Then the radiation density above the surface of the water is

$$\phi = R(T)(\pi KT)^{-\frac{1}{2}} \int_0^{\infty} e^{-Y/\lambda} \cdot e^{-Y^2/4KT}\, dY$$

Evaluating this expression, we get

$$x = \frac{\phi}{R(T)} = e^{\frac{KT}{\lambda^2}} \left[1 - \alpha\left(\frac{\sqrt{2KT}}{\lambda}\right)\right]$$

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where $\alpha(X) = \frac{1}{\sqrt{2\pi}} \int_{-X}^{X} e^{-X^2/2}\, dx$

and is the probability integral.

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Thus η represents the reduction of the radiation density above the surface due to the downward diffusion of the fission products. If $4KT > \lambda^2$, then a good approximation to η is

$$\eta = \frac{\lambda}{\sqrt{\pi KT}}$$

The larger the value of T, the better is this approximation.

The question now arises as to the proper value of K. The larger K, the more rapid the diffusion, and the less the value of η. Referring to "The Oceans" by Sverdrup, Johnson and Fleming, the least value of K ever measured was in Danish Waters at depths 0-15 m. The value of K ranged from 0.02 up to 0.6. These waters are of great stability and moderate currents. The water is greatly stabilized by a saline density gradient, and the surface water is nearly fresh. A much more comparable case for our purposes is found in the Bay of Biscay. Here the depth of water was 100 meters and the values of K range from 2 to 16. It is therefore considered that K = 1 is definitely on the low side, that k = 4 is the most probable value, and K = 8 is slightly on the high side. Substituting these values, we find the following values of η at times T hours –

K = 1		K = 4		K = 8	
T	η	T	η	T	η
0.25	0.427	0.125	0.337	0.175	0.24
0.50	0.337	0.35	0.24	0.25	0.20
1.4	0.24	0.50	0.20	0.50	0.14
2.0	0.20	1.00	0.14	1.00	0.10
4.0	0.14	2.000	0.10	2.00	0.07
8.0	0.10	4.00	0.07	4.00	0.05

It will be seen that the effect of the eddy diffusion at two hours is to reduce the radioactivity by a factor 10. At four hours, the factor is 15 – 20.

Accepting the pessimistic value that 0.001 of the fission products is deposited on the sea over a circle of radius 1000 feet, the R values above this region, as it moves with the tide will be –

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T hours	1	2	4	10
R per hour	560	200	70	18

These are considered safe estimates; the actual values may well be less even by a factor as much as 10.

Shot B

The radiation hazards in this shot are of course much more severe than in Shot A. The main factors that control the time at which the central region becomes safe for entry are the tide, and the splashing of radioactive water over the ships which do not sink.

The following are considered reasonable guesses; no evidence exists on which to formulate better calculations:

Initially, the fission products will be distributed uniformly through a cylinder of radius 1500 feet, going to the bottom. About 5% of the products will be found in the water. Turbulent diffusion does not help reduce the radiation above the water, except to a very slight degree by spreading the region. This spread however is negligible.

The radiation density above the water, allowing for the mean free path of the γ-rays in water is

$$R(\text{per hour}) = \frac{500}{T}$$

Even after 10 hours, the radiation is down only to 50 R per hour over the water. The radiation in the ships is unpredictable.

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